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Study of the $B^- \to J/\psi\, K^-\pi^+\pi^-$ Decay and Measurement of the $B^- \to X(3872)K^-$ Branching Fraction.

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We study the decay $B^- \to J/\psi K^- \pi^+ \pi^-$ using 117 million $B\bar{B}$ events collected at the $\Upsilon(4S)$ resonance with the BaBar detector at the PEP-II e^+e^- asymmetric-energy storage ring. We measure the branching fractions $\mathcal{B}\ (B^- \to J/\psi K^- \pi^+ \pi^-) = (116 \pm 7(stat.) \pm 9(syst.)) \times\ 10^{-5}$ and $\mathcal{B}\ (B^- \to X(3872) K^-) \times \mathcal{B}\ (X(3872) \to \mathrm{J}/\psi \pi^+ \pi^-) = (1.28 \pm 0.41) \times 10^{-5}$ and find the mass of the $X(3872)$ to be $3873.4 \pm 1.4 \mathrm{MeV/c^2}$. We search for the h_c narrow state in the decay $B^- \to h_c K^-$, $h_c \to J/\psi \pi^+ \pi^-$ and for the decay $B^- \to J/\psi D^0 \pi^-$, with $D^0 \to K^- \pi^+$. We set the 90% C.L. limits $\mathcal{B}\ (B^- \to h_c K^-) \times \mathcal{B}\ (h_c \to J/\psi \pi^+ \pi^-) < 3.4 \times 10^{-6}$ and $\mathcal{B}\ (B^- \to J/\psi D^0 \pi^-) < 5.2 \times 10^{-5}$.

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The study of B decays to final states containing charmonium and strange mesons is especially suited to the search for new charmonium states and for intrinsic charm. In particular, the decay $B^- \to J/\psi K^- \pi^+ \pi^-$ [1] can occur via the production of charmonium states decaying into $J/\psi \pi^+ \pi^-$ or possibly via $B^- \to J/\psi D^0 \pi^-$, with $D^0 \to K^-\ \pi^+$. Recently the Belle [2] and CDF [3] collaborations have observed a new state, the $X(3872)$, decaying into $J/\psi \pi^+ \pi^-$. This state is a charmonium candidate, the 1^3D_2 or 1^3D_3 [4], with $J^{PC} = 2^{--}$ or $J^{PC} = 3^{--}$, or even possibly a molecule of charmed D and D^* mesons [5]. In this Letter, using 117million $\Upsilon(4S)$ decays into $B\overline{B}$ pairs, we confirm the observation of the $X(3872)$ and search for the unconfirmed charmonium $1P_1$ state $h_c(3526)$ [6]. In addition, we study final states involving D mesons to test models developed to explain the excess of low momentum J/ψ mesons in inclusive B decays [7].

The data were collected at the PEP-II asymmetric-energy e^+e^- B-factory with the *BABAR* detector, which is fully described elsewhere [9]. The detector includes a silicon vertex tracker and a drift chamber in a 1.5-T solenoidal magnetic field, which detect charged particles and measure their momentum and energy loss. Photons, electrons, and neutral hadrons are detected in a CsI(Tl)-crystal electromagnetic calorimeter. A ring-imaging Cherenkov detector is used for particle identification. Penetrating muons and neutral hadrons are identified by resistive-plate chambers in the steel of the flux return. We use a Monte Carlo simulation of the *BABAR* detector based on GEANT4 [10] to validate the analysis procedure and to estimate efficiency corrections.

The event reconstruction and selection follow closely those described in an earlier paper [11]. The present analysis has been optimized to maximize the sensitivity to $B^- \to J/\psi K^- \pi^+ \pi^-$ decays. We reconstruct $J/\psi \to e^+e^-$ candidates from pairs of tracks selected with criteria that are 98% (7%) efficient for electrons (pions). To account for energy losses, we combine the electron pairs with bremsstrahlung-photon candidates and use an asymmetric mass window, $2.95 < m_{ee(\gamma)} < 3.14\,\mathrm{GeV}/c^2$. We reconstruct $J/\psi \to \mu^+\mu^-$ candidates from pairs of tracks selected with criteria that are 77% (8%) efficient for muons (pions), satisfying $3.06 < m_{\mu\mu} < 3.14\,\mathrm{GeV}/c^2$. The nominal J/ψ mass [12] is imposed as a constraint on J/ψ candidates, thereby improving the resolution on the B mass and on any charmonium states in its decay. Kaons are identified using criteria that have an efficiency of 97%, with a 15% pion-misidentification rate. B-meson candidates are formed by combining a J/ψ candidate with a kaon candidate and two additional oppositely charged tracks. To suppress further the background from light-quark production, which is characterized by back-to-back jets, the angle θ_T between the thrust axes of the reconstructed B candidate and the rest of the event in the center-of-mass system is required to satisfy $|\cos\theta_T| < 0.8(0.9)$ for $J/\psi \to e^+e^-$ $(J/\psi \to \mu^+\mu^-)$ candidates.

Signal and combinatorial background are discriminated using two kinematic variables: the beam-energy–substituted mass, $m_{\mathrm{ES}} \equiv \sqrt{(\sqrt{s}/2)^2 - {p_B^*}^2}$, and the difference of the B candidate's measured energy from the beam energy, $\Delta E \equiv E_B^* - (\sqrt{s}/2)$. Here E_B^* (p_B^*) is the energy (momentum) of the B candidate in the center-of-mass frame and $\sqrt{s}$ is the total center-of-mass energy. The signal region is defined to be $|\Delta E| < 3\sigma$, where the resolution σ, determined with data, is 12 MeV. A binned likelihood fit to the m_{ES} distribution (Fig. 1(a)) is used to separate the signal, taken as a Gaussian distribution with a fitted width of about $2.5\,\mathrm{MeV}/c^2$, plus a small tail to account for energy losses [14], from the combinatorial background distributed as an ARGUS threshold function [15]. We have checked with Monte Carlo simulation that there is no significant background from B decays that has the same m_{ES} distribution as the signal.

To reduce systematic uncertainties, we measure

$$\begin{aligned} R &= \frac{\mathcal{B}(B^- \to J/\psi K^- \pi^+ \pi^-)}{\mathcal{B}(B^- \to \psi(2S)\ K^-)} \\ &= \frac{N_{events}}{N_{\psi(2S)}} \frac{\epsilon_{\psi(2S)}}{\epsilon} \times \mathcal{B}(\psi(2S) \to J/\psi \pi^+ \pi^-), \end{aligned} \qquad (1)$$

where $N_{events} = 2540 \pm 72$ is the number of $B^- \to J/\psi K^- \pi^+ \pi^-$ signal events extracted from the fit to the m_{ES} distribution. The number of $\psi(2S)$ events, $N_{\psi(2S)} = 556 \pm 30$, is obtained by fitting $m_{J/\psi\pi\pi}$ distribution, after subratcting combinatorial background, with two Gaussian distributions representing the $\psi(2S)$

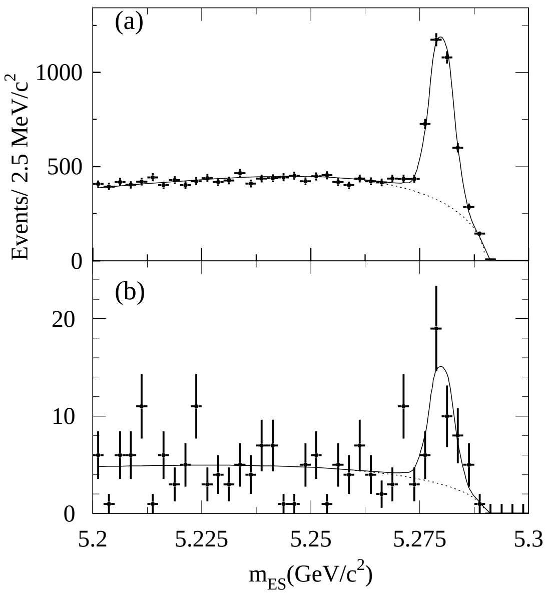

FIG. 1: Distribution of $m_{\rm ES}$ for (a) $B^- \to J/\psi K^- \pi^+ \pi^-$ candidates, and (b) events in the $X(3872)$ region, $3862 < m_{J/\psi\pi\pi} < 3882\,{\rm MeV}/c^2$. The solid curves represent the binned likelihood fits described in the text; the combinatorial components are indicated by the dashed curves.

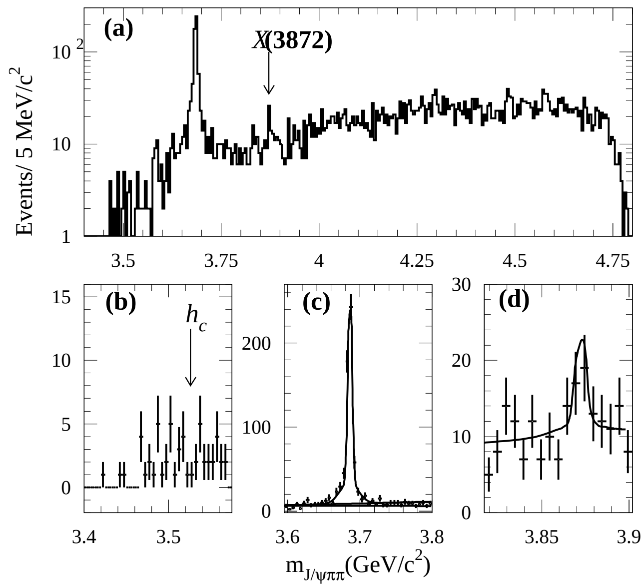

FIG. 2: Distribution of $m_{J/\psi\pi\pi}$ (a) in the entire range, (b) in the h_c region, (c) at the $\psi(2S)$, and (d) in the region of the $X(3872)$ with the projection of the unbinned likelihood fit superimposed. The requirement $m_{\rm ES} > 5.27\,{\rm GeV}/c^2$ is applied.

signal and a flat distribution representing the remaining background. (Fig. 2(c) shows the corresponding unsubtracted distribution). Throughout this Letter the distributions after combinatorial-background subtraction are obtained by fitting the $m_{\rm ES}$ distribution of the events within each bin of the variable of interest ($m_{J/\psi\pi\pi}$ in this case). The binned χ^2 fit gives a resolution on $m_{J/\psi\pi\pi}$ of $3.1 \pm 0.2\,{\rm MeV}/c^2$ for the core Gaussian containing 70% of the events and $12 \pm 3\,{\rm MeV}/c^2$ for the broader Gaussian. The total $B^- \to J/\psi K^- \pi^+ \pi^-$and the $\psi(2S)$ selection efficiencies, ϵ and $\epsilon_{\psi(2S)}$, are extracted from Monte Carlo simulation: we obtain $\epsilon_{\psi(2S)}/\epsilon = 1.17 \pm 0.03$. We use $\mathcal{B}(\psi(2S) \to J/\psi \pi^+\pi^-) = (31.8 \pm 1.0)\%$ [12].

We estimate the systematic error due to the choice of the signal $m_{\rm ES}$ shape function by replacing it with a simple Gaussian. We estimate the uncertainty on the fit to the $m_{J/\psi\pi\pi}$ distribution by using the signal resolution function as measured on Monte Carlo and by varying the background shape. Including all these errors, we measure $R = 1.70 \pm 0.10(stat.) \pm 0.09(syst.)$ which, combined with $\mathcal{B}(B^- \to \psi(2S)\ K^-) = (6.8 \pm 0.4) \times 10^{-4}$ [12], yields

$$\mathcal{B}(B^- \to J/\psi K^- \pi^+ \pi^-) \ = \ (116 \ \pm \ 7(stat.) \pm 9(syst.)) \times 10^{-5}. \quad (2)$$

To investigate the possible presence of narrow charmonium states decaying to $J/\psi \pi^- \pi^+$, we have studied the distribution in $m_{J/\psi\pi\pi}$ (Fig. 2(a)). We observe an excess in the region of the $X(3872)$ (Fig. 2(d)), but do not find any excess in the h_c region (Fig. 2(b)). The mass of the $X(3872)$ state is extracted from an unbinned maximum likelihood fit to the two-dimensional distribution in $m_{\rm ES}$ and $m_{J/\psi\pi\pi}$. The probability density function (PDF) is taken to be the sum of four terms. The first three describe $B^- \to J/\psi K^- \pi^+ \pi^-$ decays that peak when $m_{\rm ES}$ is the mass of the B-meson. The PDF of these three terms contains a Gaussian function in $m_{\rm ES}$ times a function of $m_{J/\psi\pi\pi}$ that describes: 1) non-resonant events, distributed as a first order polynomial; 2) $\psi(2S)$ candidates, distributed as a double-Gaussian resolution function around a mean value that is allowed to float; and 3) $X(3872)$ candidates, with the same resolution function as the $\psi(2S)$ but with a mass that floats relative to the $\psi(2S)$ mass. The measurement of mass difference allows us to neglect systematic errors on the absolute mass scale. The fourth term of the PDF describes the combinatorial background, distributed as an ARGUS threshold function in $m_{\rm ES}$ and as a first order polynomial in $m_{J/\psi\pi\pi}$. From the $\psi(2S)$ mass value, $m_{\psi(2S)} = 3685.96 \pm 0.09\,{\rm MeV}/c^2$ [12], we find $m_{X(3872)} = 3873.4 \pm 1.4\,{\rm MeV}/c^2$, consistent with the previous measurements by Belle [2] and CDF [3].

The measurement of the branching fraction $\mathcal{B}(B^- \to X(3872) K^-) \times \mathcal{B}(X(3872) \to J/\psi \pi^+ \pi^-)$ is performed with a counting technique. We select events

in a $\pm 10\,\mathrm{MeV}/c^2$ window around $m_{J/\psi\pi\pi}$=3872 MeV/c^2, and find the number of events with $m_{\rm ES} > 5.27\,\mathrm{GeV}/c^2$ to be $N_{data} = 63$. We estimate the number of these events due to combinatorial background ($N_{comb} = 22.0 \pm 4.3$) from a fit to the $m_{\rm ES}$ distribution (Fig. 1(b)). The number of events with the same final state $B^- \to J/\psi K^-\pi^+\pi^-$, but not belonging to the $X(3872)$ signal, is estimated to be $N_{peak} = 10.5 \pm 3.2$ from a fit to the $m_{\rm ES}$ distribution in the symmetric sideband $15 < |m_{J/\psi\pi\pi} - 3872| < 45\,\mathrm{MeV}/c^2$. The resulting number of signal events is 30.5 which agrees within the errors with the number of signal events, 25.4 ± 8.7, obtained from the fit to the $X(3872)$ in Figure 2(d). The branching fractions are determined using a frequentist confidence level [13]. This technique treats properly the small number of events and includes the systematic errors directly in the computation of confidence intervals or limits. The confidence level, α, a function of $\mathcal{B}(B^- \to X(3872)K^-) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ is computed as the fraction of times that a random number generated according to a Poisson distribution with a mean value of

$$\mu = N_{bkg} + N_{\psi(2S)}\epsilon_w \times \frac{\mathcal{B}(B^- \to X(3872)K^-)\mathcal{B}(X(3872) \to \mathrm{J}/\psi\pi^+\pi^-)}{\mathcal{B}(B^- \to \psi(2S)K^-)\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} \quad (3)$$

exceeds the observed data. For a given value of $\mathcal{B}(B^- \to X(3872)K^-) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-)$ the variables N_{bkg}, $N_{\psi(2S)}$, $\mathcal{B}(B^- \to \psi(2S)K^-)$, and $\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)$ are randomly generated to determine a value of μ, which is then used in a Poisson distribution to generate a new value of the number of detected events. The generation is repeated many times and the fraction of times the random number exceeds $N_{data} = 63$ yields the value of α. The variables N_{bkg}, $N_{\psi(2S)}$, $\mathcal{B}(B^- \to \psi(2S)K^-)$, and $\mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)$, are generated according to Gaussian distributions. The mean of $N_{\psi(2S)}$ is 556 and $\sigma = 30$. The mean of N_{bkg} is $N_{comb} + N_{peak} = 32.5$ and $\sigma = 5.9$, which includes a systematic error on N_{peak} calculated by varying the boundaries of the sideband. We use published values [12] for the remaining branching fractions and their errors, assumed to be Gaussian. Finally, $\epsilon_w = (92 \pm 1)\%$ is the fraction of events that fall in the $m_{J/\psi\pi\pi}$ window, from applying the same mass window cut to the $\psi(2S)$ and assuming the same efficiency. From the values of $\mathcal{B}(B^- \to X(3872)K^-)$ at which $\alpha = 16\%$ and 84% we measure

$$\mathcal{B}(B^- \to X(3872)K^-) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (1.28 \pm 0.41) \times 10^{-5}. \quad (4)$$

The probability that the observed events are a background fluctuation in the considered mass window is 5.4×10^{-4}, corresponding to 3.5 Gaussian standard deviations. As a check, we performed the same measurement on the $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$ samples separately, obtaining $\mathcal{B}(B^- \to X(3872)K^-) \times \mathcal{B}(X(3872) \to \mathrm{J}/\psi\pi^+\pi^-) = (1.94 \pm 0.62) \times 10^{-5}$ and $(0.52 \pm 0.46) \times 10^{-5}$ respectively, consistent within 1.8 standard deviations.

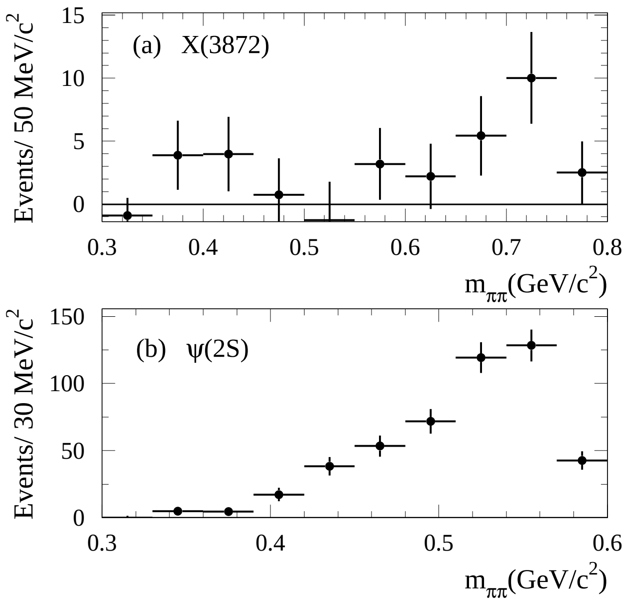

FIG. 3: Distribution of $m_{\pi^+\pi^-}$(a) at the $X(3872)$ and (b) at the $\psi(2S)$, after subtraction of combinatorial and peaking background.

The decay of a charmonium state into $\rho J/\psi$ is a strongly suppressed isospin-violating process. In order to investigate the nature of the $X(3872)$ state, we plot the invariant mass of the $\pi^+\,\pi^-$ system in both the $X(3872)$ and the $\psi(2S)$ region (Fig. 3). In the $\psi(2S)$ case, the events are concentrated near the kinematic limit. Such behavior is not excluded for the $X(3872)$, but the statistics are too small to allow a clear conclusion. Measuring both the $m_{\pi^+\pi^-}$ and angular distributions with significantly greater statistics would provide important information on the nature of the $X(3872)$.

The search for the h_c is performed with the same frequentist technique in a $\pm 10\,\mathrm{MeV}/c^2$ mass window centered on $m_{J/\psi\pi\pi} = 3526\,\mathrm{MeV}/c^2$ [6]. With $N_{data} = 9$, $N_{comb} = 6.9 \pm 3.5$, $N_{peak} = 0.6 \pm 1.5$, and assuming the same efficiency $\epsilon_w = (92 \pm 1)\%$, we set a 90% C.L. limit $\mathcal{B}(B^- \to h_c K^-) \times \mathcal{B}(h_c \to J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$. The probability that we would see a signal as large as the one observed from background fluctuations alone is 39%.

Finally, we search for $B^- \to J/\psi D^0\pi^-$ decays with $D^0 \to K^-\pi^+$. The decay $D^0 \to K^-\pi^+$ would have an r.m.s. width of $5.4\,\mathrm{MeV}/c^2$ in $m_{K^-\pi^+}$ as determined from Monte Carlo. We study this distri-

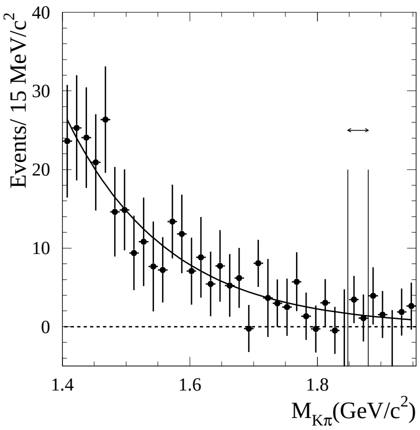

FIG. 4: Distribution of $m_{K^-\pi^+}$ in events $B^- \to J/\psi\, K^-\pi^+\pi^-$, with combinatorial background removed. Overlaid is an exponential fit. The arrow indicates the 3σ region expected for $D^0 \to K^-\pi^+$.

bution in the same way we studied $m_{J/\psi\pi\pi}$. The $m_{K^-\pi^+}$ combinatorial-subtracted distribution (Fig. 4) shows no significant structure, and it is therefore used to set a limit. We fit the background from other $B^- \to J/\psi\, K^-\pi^+\pi^-$ decays with an exponential function of $m_{K^-\pi^+}$ and obtain $N_{peak} = 2.9 \pm 1.4$. The frequentist approach described above, with $N_{data} = 10$, $N_{comb} = 7.8 \pm 2.8$ and $\epsilon/\epsilon_{\psi(2S)} = 1.00 \pm 0.07$ yields the 90% C.L. limit $\mathcal{B}(B^- \to J/\psi\, D^0\pi^-) < 5.2 \times 10^{-5}$. This upper limit rules out the explanation of the inclusive J/ψ momentum spectrum with intrinsic charm proposed in [8].

In summary, we measured $\mathcal{B}(B^- \to J/\psi\, K^-\pi^+\pi^-) = (116 \pm 7(stat.) \pm 9(syst.)) \times 10^{-5}$ with an error almost a factor two smaller than the present average [12] and we confirmed the observation of $B^- \to X(3872)K^-$ [2, 3]. We measured $\mathcal{B}(B^- \to X(3872)K^-) \times \mathcal{B}(X(3872) \to J/\psi\pi^+\pi^-) = (1.28 \pm 0.41) \times 10^{-5}$ and $m_{X(3872)} = 3873.4 \pm 1.4\,\mathrm{MeV}/c^2$. We also studied the $m_{J/\psi\pi\pi}$ and $m_{K^-\pi^+}$ distributions searching for $B^- \to h_c K^-$ and $B^- \to J/\psi\, D^0\pi^-$ decays and set limits on their branching fractions, $\mathcal{B}(B^- \to h_c K^-) \times \mathcal{B}(h_c \to J/\psi\pi^+\pi^-) < 3.4 \times 10^{-6}$ and $\mathcal{B}(B^- \to J/\psi\, D^0\pi^-) < 5.2 \times 10^{-5}$ at 90% C.L.

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